Chapter 3

The Benefits and Pitfalls of Geographic Information Systems in Marine Benthic Habitat Mapping

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Abstract

The application of geographic information system (GIS) technology to the characterization of marine benthic habitats has greatly increased the speed and resolution of seafloor mapping efforts. GIS is a powerful tool for the visualization and imaging of seafloor characteristics and has also proven useful for the quantification of mapped substrate types, determination of slope inclination and rugosity, and other spatial analyses. With the use of GIS, geologists and digital cartographers can create marine benthic habitat maps to assist scientists and policy-makers in the management of commercial groundfish stocks and the designation of marine protected areas. However, without a complete understanding of mapping procedures and the technology used to obtain source data (e.g., multibeam swath bathymetric and backscatter imagery), maps and GIS products may be misinterpreted and used in ways that are inappropriate or misleading.

Introduction

The use of geographic information systems (GISs) has proven to be extremely effective in the compilation and presentation of maps of various types and scales. GIS technology (especially by ESRI®) is presently the tool of choice for the scientific community involved in the mapping of marine benthic habitats because of its flexibility and ease in adding, modifying, and analyzing data. However, a lack of proper understanding and documentation of the quality, manipulation, and limitations of source data and derivative habitat interpretations is leading to confusion and potentially inappropriate use of habitat maps presented

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in GIS. Though the use of GIS in seafloor mapping is still in its early stages of development, protocols must be established to more clearly identify data type, quality, interpretive processes, and authors of habitat interpretations (genealogy).

Marine benthic habitat maps are critical to state and federal fisheries agencies for the development of management and conservation policies and as a basis for habitat-related studies. These maps play a crucial role in the evaluation, extension, and selection of marine protected areas (MPAs) that are being established to conserve overexploited groundfish species (Yoklavich et al., 1997; O'Connell et al., 1998). The demand for these maps and related GIS products has led to a community-wide compilation and interpretation frenzy. In many cases, groups and agencies have rapidly incorporated, and possibly incompletely documented, GIS datasets that are being utilized by government, academic, industry and non-governmental organizations in mapping and monitoring marine benthic habitats and developing management plans for groundfish species.

Although GIS has facilitated a great increase in the quality and quantity of marine benthic habitat maps, in some cases users are unaware of its limitations. Even when Federal Geographic Data Committee (FGDC) compliant metadata was included, our map products have occasionally been misinterpreted and incorrectly used because our interpretive processes and/or the quality of source data was not fully understood. Given the widespread compilation and use of habitat maps and their importance in fisheries management, this could become a serious problem. The objective of this paper is therefore to briefly discuss the advantages, or benefits, and disadvantages, or pitfalls, encountered in using GIS in mapping marine benthic habitats. Possible solutions to the problems outlined herein are also suggested.

Discussion

Habitats: Definitions

The word "habitat" has been used in many ways and the concept has inconsistent connotations to scientists of different disciplines. The following basic definition is found in the *Merriam-Webster's Dictionary* (2004): "1.a. the place or environment where a plant or animal naturally or normally lives and grows. 2. the place where something is commonly found." The *Glossary of Geology* (Bates and Jackson,1980) provides an only slightly more specific definition: "the particular environment where an organism or species tends to live; a more locally circumscribed portion of the total environment." Essential Fish Habitat is defined in the Sustainable Fisheries Act (1996) as: "waters and substrate necessary for spawning, breeding, feeding or growth to maturity," which again is so generally descriptive as not to be very useful. Due to the vague nature of this verbiage, the definition of marine habitats by NOAA has been legally challenged and is in the process of being re-defined. None of these general descriptors is useful in characterizing marine benthic habitats, which are necessarily defined on a species-specific basis and may be highly variable for different populations or life stages.

In this paper, we consider a marine benthic habitat as a set of seafloor conditions that is commonly associated with a species or local population thereof. Subsets of the overall habitat of a species may be utilized differentially for foraging (subsistence), refuge, reproduction or rest. Physical (e.g., temperature, current speed and direction, depth), chemical (e.g., salinity, nutrients, minerals), geological (e.g., substrate type, seafloor morphology) and biological parameters (e.g., species density, % cover of sessile or encrusting flora and fauna) can be used to determine a species' habitat associations. These various datasets can be presented in GIS in both tabular (attribute) and visual form. Multiple layers can be overlaid to depict the various seafloor conditions in a coordinated fashion and used to interpret marine benthic habitats.

Since specific habitat associations for a species are not often known during the compilation of and interpretation of seafloor data, it is not appropriate to describe interpretive maps of the seafloor as "habitat" maps. We therefore propose the term "potential habitat" to describe a set of distinct seafloor conditions that may be utilized differentially by a species. Once habitat associations are determined, they can be used to create maps that depict the actual distribution and abundance of a species in relation to its known habitat types.

Habitats: Characterization

There are two basic approaches to characterizing habitats. One is the top-down approach advocated by biologists and the other is the bottom-up approach characteristic to geologists. Biologists pioneered the description of habitats and developed habitat characterization schemes based on flora and fauna in the terrestrial and coastal environment (CEC 1997; FGDC 1997). These schemes typically describe forest, brush, and micro-vegetation from the crest of mountains to the intertidal zones, with substrate being the third or fourth descriptor. However, while flora and fauna change, substrate, or geology, may often be continuous from onshore to offshore.

A bottom-up classification scheme can link terrestrial and seafloor conditions in a continuous fashion, a process that is much more difficult to accomplish with biological parameters. In seafloor areas (such as the deep sea) where demersal fauna and flora are sparse or non-existent, biology may be absent or restricted to infauna. Organisms that are present in these regions are often difficult to identify or quantify. Conversely, seafloor conditions can be efficiently imaged geophysically and described geologically due to tremendous advances in remote sensing technology. As a result of these considerations, a geological bottom-up characterization of habitats seems more appropriate for deep-water (>~30 m) marine benthic regions.

A GIS-Compatible Classification Scheme for Potential Marine Benthic Habitats

We constructed a detailed, GIS-compatible classification scheme for the characterization of potential marine benthic habitats. Although the classification scheme is in flux, it is presented for reference purposes along with an explanation for its use (Appendices 3.1, 3.2). This scheme is generally based on geomorphological and physiographical scales, depth, seafloor induration (hardness), texture and sessile biology. Potential habitats are divided into four types based on size (scale) and depth: Mega-, Meso-, Macro- and Microhabitats after Greene et al. (1999). Mega-, meso-, and macrohabitats are typically interpreted from seafloor imagery (e.g., sidescan sonar, multibeam imagery) or geologic data. Imaging and characterization of microhabitats is typically more difficult and time-consuming and is usually best accomplished from in situ or video observations.

Data Sources and Map Construction

Many different types of data are being used to characterize potential and actual marine benthic habitats (Greene et al., 1995, 1999, 2000; Yoklavich et al., 1995, 2000; Auzende and Greene, 1999; Gordon et al., 2000; Todd et al., 2000; Kostylev et al., 2001). These data range from previously constructed seafloor geologic, geomorphic, geophysical, sediment, biologic and bathymetric maps to remotely collected seafloor imagery (e.g., single beam echosounder, multibeam bathymetric and backscatter, side-scan sonar, and seismic reflection profile, LIDAR, laser-line scan, and hyperspectral data) and in situ observational and photographic (video and still photo) data obtained with the use of submersibles, ROVs, camera sleds, or by free diving. As previously mentioned, these data are used for the interpretation of seafloor morphology and substrate types that can be represented as either potential habitats or actual habitats. Thematic maps depicting substrate types, benthic habitats, physiography, bathymetry, and morphology can be constructed from interpretation of remotely and in situ collected data. Various spatial analysis tools enable an interpreter using GIS to construct maps detailing seafloor complexity and seafloor slope, and to quantify substrate and morphologic features useful in determining critical habitat parameters. In the following section, we discuss some of the advantages and disadvantages of the contemporary practice of mapping potential or actual marine benthic habitats.

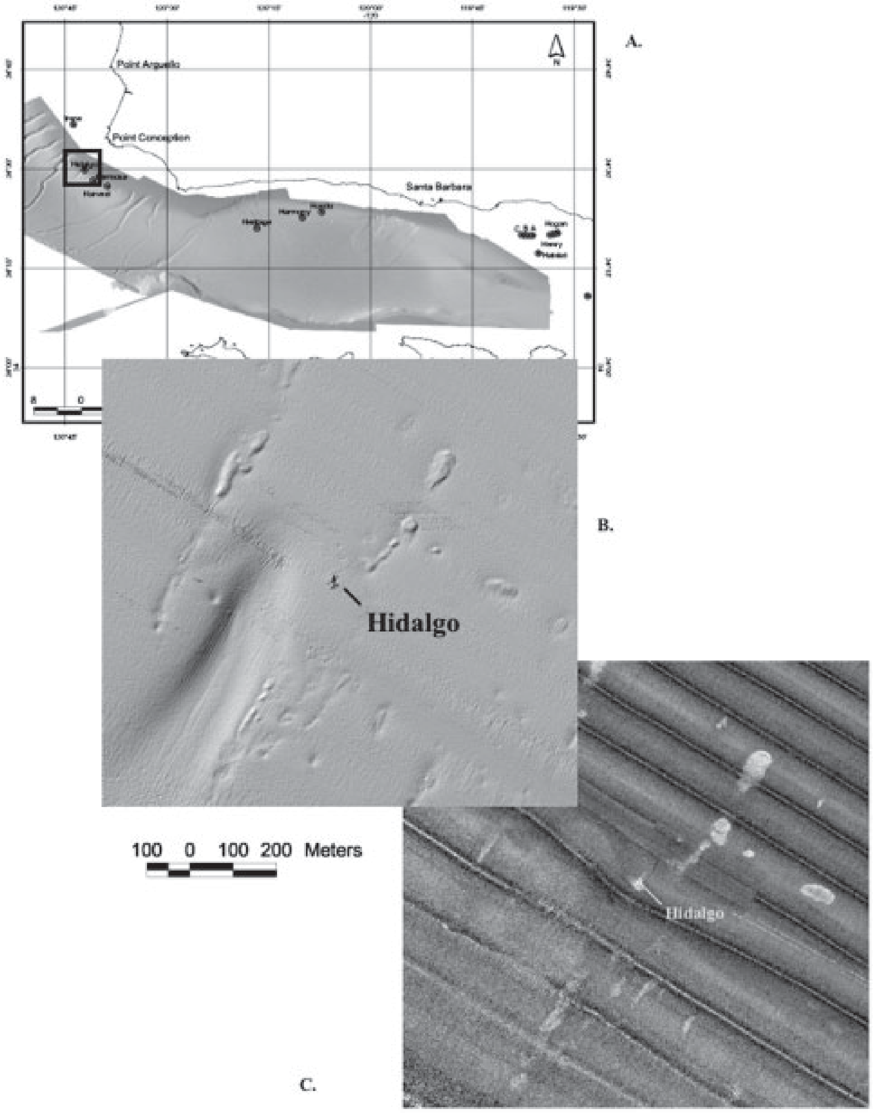

Figure 3.1. (a) Simrad EM 300 (30 kHz) color-shaded multibeam bathymetric image of oil platforms, including Hidalgo, in the Santa Barbara region. Box shows location of (b) and (c). (b) Simrad EM 300 (30 kHz) multibeam artificial sun-illuminated bathymetric image of the seafloor around the Hidalgo oil platform in Santa Barbara Channel. Data courtesy of the Monterey Bay Aquarium Research Institute. See (a) for location. (c) Backscatter image obtained with a Simrad EM 300 (30 kHz) system showing seafloor texture around the Hidalgo oil platform; bright areas are hard mounds, darker areas are unconsolidated sediment. Data courtesy of the Monterey Bay Aquarium Research Institute. See (a) for location.

Advantages (Benefits)

GIS is an excellent tool for developing basemaps and for layering various thematic datasets above and below a basemap. Often in deep-water habitat mapping, the basemap is a bathymetric map of some sort. Typical source data for basemaps consist of either a bathymetric contour map or a multibeam bathymetric map, commonly presented as an artificial, sun-illuminated relief map (Fig. 3.1a, b), which is digitally constructed from x, y, z data that represent accurately positioned soundings. These types of maps are easily displayed using GIS. The next type of map, or overlay to the basemap, is typically multibeam backscatter (Fig. 3.1c) or side-scan sonar (Fig. 3.2) imagery, which provides information about seafloor texture and substrate types. If geologic data and/or geologic maps are available, these data can then be incorporated into a GIS project as another layer. Many other datasets and maps can also be included and represented. Potential marine benthic habitats are interpreted from these multiple data layers and the ultimate interpretive map consists of polygons that have been attributed to distinct habitat types (Fig. 3.3; see page XX).

Ease of geo-referencing and incorporating maps and data from a variety of sources is a distinct advantage of GIS and facilitates the inclusion of both analog data, which can be scanned and digitized, and

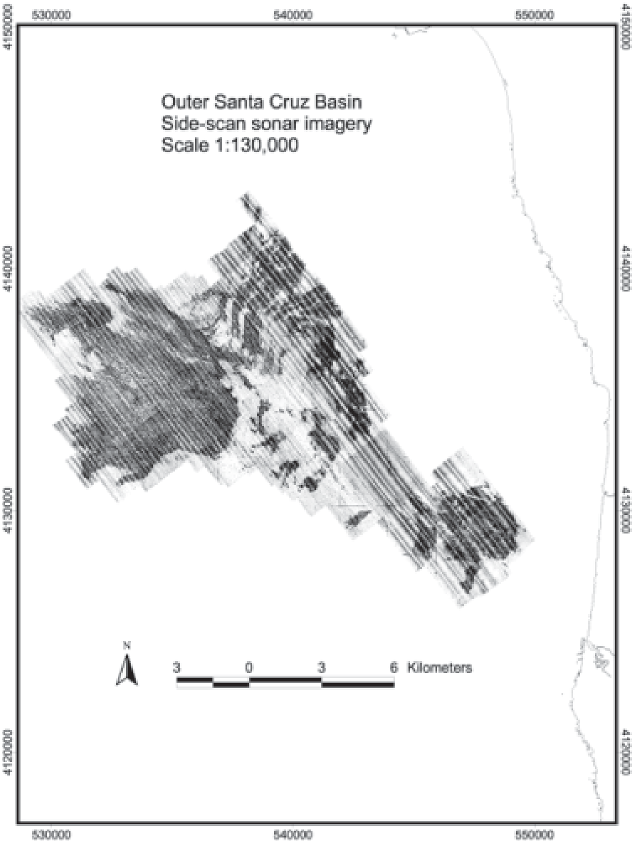

Figure 3.2. Example of a side-scan sonar mosaic. This dataset was collected on the continental shelf north of Santa Cruz, California. Dark areas are hard rock exposures; light areas are unconsolidated sediment (likely sand). Data courtesy of Delta Oceanographics, Inc. and Fugro-Pelagos, Inc.

digital data. This allows for the utilization of historical data sources that may otherwise be overlooked. Once incorporated into a GIS project, these data can be layered and used collectively as a basis for habitat interpretations.

GIS is also a convenient tool for updating habitat maps. Because of the ease of inputting and layering geo-referenced data, habitat maps can be readily updated once new data become available. This enables users to conduct time-series analyses that may be essential to monitoring studies. These studies are especially important in areas where dynamic seafloor processes occur and may temporally alter habitats (Fig. 3.4; see page XX).

Excellent quantification and spatial analysis tools are available in GIS programs. With these tools, polygon areas can be quantified and can be summed by habitat type to determine habitat-specific areas (Fig. 3.5; see page XX). Seafloor slope can also be calculated using x,y,z data typically collected with multibeam systems (Fig. 3.6; see page XX). Rugosity, based on neighborhood statistics, can also be calculated with these data. Maps derived from these analyses can be constructed and represented as thematic layers in a GIS project.

Disadvantages (Pitfalls)

Probably the most serious problem in the use of GIS for marine benthic habitat mapping is the lack of attention paid to the type and quality of data used to construct a habitat map and the incomplete documentation of the history of data collection, modification, interpretation, and genealogy. This type of information is included as metadata in either read-me files or, more recently, compiled in ArcCatalog®. However, metadata is often isolated from GIS map projects and may not be readily accessible or considered by the users. Even when it is easily incorporated (e.g., ArcGIS®) it is presented in a lengthy, written format. One of the main benefits and primary uses of GIS programs is to facilitate the visualization and incorporation of a wide variety of data sources into a project. Metadata (especially for data type and quality) should therefore be displayed in a similar format to increase utilization and comprehension by the user.

Without detailed knowledge of data type and the quality, it is difficult to assess the accuracy of derivative habitat maps. For example, a habitat map may have been constructed from a previously published offshore geologic map that was produced from the interpretation of seismic reflection profiles and seafloor sampling (Fig. 3.7; see page XX). Although closed polygons were constructed, their resolution would be such that their boundaries in most areas are only approximately located. This map could be merged with higher resolution maps constructed from state-of-the-art multibeam bathymetry and backscatter data (Fig. 3.8; see page XX) that would then exhibit seamless polygons synthesized from all datasets (Fig. 3.9; see page XX). However, without knowledge of these facts, a user may assume that the habitat map was created from sources of equal quality and therefore should be of uniform accuracy. It is easy to imagine the pitfalls of this thinking, which could adversely skew management regulations or other decision-making tasks.

A critical component in the creation of habitat maps is the scale at which the source data were interpreted. Without this information, it becomes very difficult to determine accuracy of habitat interpretations. Although it is possible to infer relative differences in data resolution by the differing sizes and shapes of delineated polygons (Fig. 3.9), the true differences are unobtainable from habitat maps or metadata.

Solutions

While metadata is useful for referencing technical information, it is not visually informative and therefore often overlooked or not well understood, especially by managers and scientists who may not have a technical understanding of GIS. Some of the most important information needed, such as data type, quality, and scale, are best presented visually rather than in a written format. We therefore propose that a data type and quality layer be developed that would correspond to all marine habitat maps presented in a GIS product. This layer would essentially be a map (Fig. 3.10; see page XX) that would exhibit area (with tracklines when appropriate), type, and quality of data used in the interpretation of marine benthic habitat maps. Information on data source, collection, associated publications, scale, and genealogy could be listed in the attribute table for this map layer and easily accessed for polygons or regions of interest. This type of metadata presentation would more efficiently and effectively serve GIS map users in evaluating accuracy and quality and determining data sources.

Conclusions

GISs provide excellent tools for the compilation and presentation of marine benthic habitat maps. They are especially valuable in exhibiting various thematic layers that can be used to compile and manipulate different and disparate datasets in a manner that allows for the construction of very comprehensive habitat and other thematic maps (Fig. 3.10). However, the lack of a convenient protocol to clearly and illustratively convey information such as source data type, quality, scale, and genealogy hampers the ability of a user to assess the accuracy and quality of the resultant habitat maps. Inclusion in metadata is a necessary, but circuitous way of displaying this critical information. We, therefore, propose a protocol that consists of a distinct layer within a GIS project that exhibits and lists data type, quality, source, collection date, interpretation scale(s), genealogy and associated publications (bibliography) used in the construction of marine benthic habitat maps (Fig. 3.11; see page XX). If adapted by the marine benthic habitat mapping community, a standard methodology would exist to better determine and understand the specific details of seafloor datasets used in the characterization and assessment of marine benthic habitats.

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APPENDIX 3.1

Key to Marine Benthic Habitat Classification Scheme

(modified after Greene et al., 1999)

Megahabitat – Use capital letters (based on depth and general physiographic boundaries; depth ranges approximate and can be modified according to study area).

A = Apron, continental rise, deep fan or bajada (3000-4000 m)
B = Basin floor, Borderland type (1000-2500 m)
E = Estuary (0-50 m)
F = Flank, continental slope, basin/island-atoll flank (200-3000 m)
I = Inland sea, fiord (0-200 m)
P = Plain, abyssal (4000-6000+ m)
R = Ridge, bank or seamount (crests at 200-2500 m)
S = Shelf, continental or island (0-200 m)

Seafloor induration - Use lower-case letters (based on substrate hardness).

h = hard substrate, rock outcrop, relic beach rock or sediment pavement
m = mixed (hard & soft substrate)
s = soft substrate, sediment-covered

Sediment types (for above indurations) - Use parentheses.

(b) = boulder
(c) = cobble
(g) = gravel
(h) = halimeda sediment, carbonate
(m) = mud, silt, clay
(p) = pebble
(s) = sand

Meso/Macrohabitat - Use lower-case letters (based on scale).

a = atoll
b = beach, relic
c = canyon
d = deformed, tilted and folded bedrock
e = exposure, bedrock
f = flat, floor
g = gully, channel
i = ice-formed feature or deposit, moraine, drop-stone depression
k = karst, solution pit, sink
l = landslide
m = mound, depression; includes short, linear ridges
n = enclosed waters, lagoon
o = overbank deposit (levee)
p = pinnacle, volcanic cone
r = rill
s = scarp, cliff, fault or slump
t = terrace
w = sediment waves
y = delta, fan
$z_{\#}$ = zooxanthellae hosting structure, carbonate reef
    1 = barrier reef
    2 = fringing reef
    3 = head, bommie
    4 = patch reef

Modifier - Use lower-case subscript letters or underscore (textural and lithologic relationship).

$_{a}$ = anthropogenic (artificial reef/breakwall/shipwreck)
$_{b}$ = bimodal (conglomeratic, mixed [includes gravel, cobbles and pebbles])
$_{c}$ = consolidated sediment (includes claystone, mudstone, siltstone, sandstone, breccia, or conglomerate)
$_{d}$ = differentially eroded
$_{f}$ = fracture, joints-faulted
$_{g}$ = granite
$_{h}$ = hummocky, irregular relief
$_{i}$ = interface, lithologic contact
$_{k}$ = kelp
$_{l}$ = limestone or carbonate
$_{m}$ = massive sedimentary bedrock
$_{o}$ = outwash
$_{p}$ = pavement
$_{r}$ = ripples
$_{s}$ = scour (current or ice, direction noted)
$_{u}$ = unconsolidated sediment
$_{v}$ = volcanic rock

Seafloor slope - Use category numbers. Typically calculated from x-y-z multibeam data. Category designations represent suggestions and can be modified by the user.

1 Flat (0-1°)
2 Sloping (1-30°)
3 Steeply Sloping (30-60°)
4 Vertical (60-90°)
5 Overhang (> 90°)

Seafloor complexity - Use category letters (in caps). Typically calculated from x-y-z multibeam slope data using neighborhood statistics and reported in standard deviation units. Category designations represent suggestions and can be modified by the user.

A Very Low Complexity (-1 to 0)

B	Low Complexity (0 to 1)
C	Moderate Complexity (1 to 2)
D	High Complexity (2 to 3)
E	Very High Complexity (3+)

Geologic Unit – When possible, the associated geologic unit is identified for each habitat type and follows the habitat designation in parentheses.

Examples:

Shp$_d$1D(Q/R) - Continental shelf megahabitat; flat, highly complex (differentially eroded) hard seafloor with pinnacles. Geologic unit = Quaternary/Recent.

Fhd_d2C (Tmm) - Continental slope megahabitat; sloping hard seafloor of deformed (tilted, faulted, folded), differentially eroded bedrock. Geologic unit = Tertiary Miocene Monterey Formation.

APPENDIX 3.2

Explanation for Marine Benthic Habitat Classification Scheme

(modified after Greene et al., 1999)

HABITAT CLASSIFICATION CODE

A habitat classification code, based on the deepwater habitat characterization scheme developed by Greene et al. (1999), was created to easily distinguish marine benthic habitats and to facilitate ease of use and queries within GIS (e.g., ArcView®, TNT Mips®, and ArcGIS®) and database (e.g., Microsoft Access® or Excel®) programs. The code is derived from several categories and can be subdivided based on the spatial scale of the data. The following categories apply directly to habitat interpretations determined from remote sensing imagery collected at the scale of tens of kilometers to one meter: Megahabitat, Seafloor Induration, Meso/Macrohabitat, Modifier, Seafloor Slope, Seafloor Complexity, and Geologic Unit. Additional categories of Macro/Microhabitat, Seafloor Slope, and Seafloor Complexity apply to areas at the scale of 10 meters to centimeters and are determined from video, still photos, or direct observations. These two components can be used in conjunction to define a habitat across spatial scales or separately for comparisons between large and small-scale habitat types. Categories are explained in detail below. Not all categories may be required or possible given the study objectives, data availability, or data quality. In these cases the categories used may be selected to best accommodate the needs of the user. If an attribute characterization is probable but questionable, it is followed by a question mark to infer a lower level of interpretive confidence.

EXPLANATION OF ATTRIBUTE CATEGORIES AND THEIR USE

Determined from Remote Sensing Imagery (for creation of large-scale habitat maps)

(1) Megahabitat – This category is based on depth and general physiographic boundaries and is used to distinguish regions and features on a scale of tens of kilometers to kilometers. Depth ranges listed for category attributes in the key are given as generalized examples. This category is listed first in the code and denoted with a capital letter.

(2) Seafloor Induration – Seafloor induration refers to substrate hardness and is depicted by the second letter (a lower-case letter) in the code. Designations of hard, mixed, and soft substrate may be further subdivided into distinct sediment types, which are then listed immediately afterwards in parentheses either in alphabetical order or in order of relative abundance.

(3) Meso/Macrohabitat – This distinction is related to the scale of the habitat and consists of seafloor features ranging from one kilometer to one meter in size. Meso/Macrohabitats are noted as the third letter (a lower-case letter) in the code. If necessary, several Meso/Macrohabitats can be included either alphabetically or in order of relative abundance and separated by a backslash.

(4) Modifier – The fourth letter in the code, a modifier, is noted with a lower-case subscript letter or separated by an underline in some GIS programs (e.g., ArcView®). Modifiers describe the texture or lithology of the seafloor. If necessary, several modifiers can be included alphabetically or in order of relative abundance and separated by a backslash.

(5) Seafloor Slope – The fifth category, represented by a number following the modifier subscript, denotes slope. Slope is typically calculated for a survey area from x-y-z multibeam data and category values can be modified based on characteristics of the study region.

(6) Seafloor Complexity – Complexity is denoted by the sixth letter and listed in caps. Complexity is typically calculated from slope data using neighborhood statistics and reported in standard deviation units. As with slope, category values can be modified based on characteristics of the study region.

(7) Geologic Unit – When possible, the geologic unit is determined and listed subsequent to the habitat classification code in parentheses.